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EVALUATION OF ADHESIVE STRENGTH BASED ON THE INTENSITY OF SINGULAR STRESS FIELD OF SINGLE LAP JOINT

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Abstract: In this study, the adhesive strength for single lap joint is investigated based on the intensity of singular stress field. First, the critical intensity of singular stress at the adhesive dissimilar joint is calculated by using finite element method (FEM) based on the experimental result. It is found that the adhesive strength can be expressed as the critical intensity of singular stress field. Then, a suitable evaluation method of adhesive strength is investigated focusing on the intensity of singular stress field. The effect of specimen geometry on the intensity of singular stress is considered. The results show that the intensity of singular stress field decreases with increasing the adherend thickness, the minimum intensity of singular stress can be obtained when the adherend thickness is large enough. The results of the deformation angle at the interface corner edge show a similar trend as in intensity of singular stress field, and the minimum deformation angle can be obtained when the adherend thickness is large enough. The usefulness of the method is investigated focusing on the deformation angle at the interface corner edge.

Keywords: Stress intensity factor; Interfaces; Deformation angle; Single lap joint

1 INTRODUCTION

Since adhesively joints are economical, practical and easy to be used; thus they have been widely used in a variety of industries. A number of studies of adhesive joints have been made so far [1-4]. The authors investigated the adhesive butt joint strength in Fig. 1 by changing the adhesive thickness and material combination [5,6]. It is found that the adhesive strength can be expressed as the critical intensity of singular stress field as $K_{\sigma c}$ =const based on the experimental results. The adhesive strengths of the single lap joint (see Fig. 2(a)) and double lap joint (see Fig.2(b)) were also investigated previouly [7]. In this result, the adhesive strength of double lap joint is not equal to the one of single lap joint as expected and is almost twice larger than the one of single lap joint. Compared with double lap joint, single lap joint testing is more stable and used conveniently. The testing method and experimental adhesive strength are prescribed by Japanese Industrial Standards (JIS) [8]. However, since the debonding strength is defined as the magnitude of the load, the strength is affected by the specimen dimension and difficult to be applied to other geometries. Therefore, it is necessary to find a suitable method to evaluation the debonding strength of single lap joint testing.

In this paper, first, the debonding strength of single lap joint will be investigated based on the experimental results [9] by using the evaluation method shown in [6]. Then, a suitable evaluation method of adhesive strength will be evaluated focusing on the intensity of singular stress field and the deformation angle appearing at the end of interface.

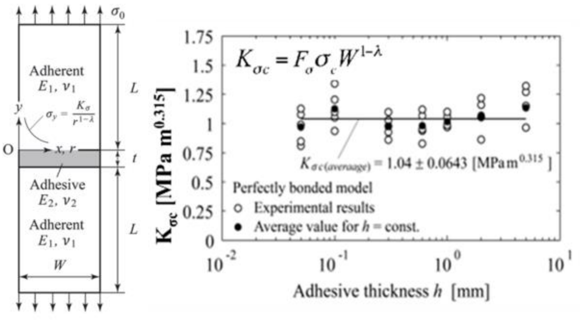

Fig.1 Adhesive strength expressed as $K_{\sigma c}$ =const for butt joint.

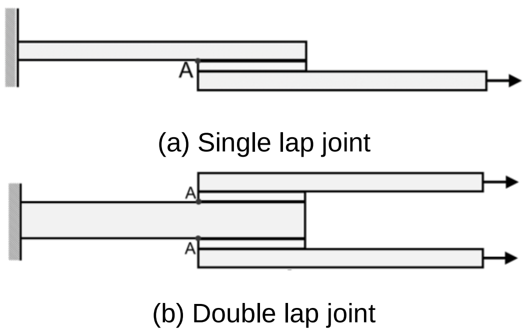

Fig.2 Single and double lap joints.

2 ADHESIVE STRENGTH EXPRESSED AS A CONSTAN CRITICAL INTENSITY OF SINGULAR STRESS $K_{\sigma c}$ FOR SINGLE LAP JOINT WITH VARYING ADHESIVE GEOMETRY l_{ad} AND t_{ad}

Figure 3 shows the schematic illustration of the analysis models. It has been reported that the singularity exists near the interface corner, and the singularity depending on the singular indexes λ_1 and λ_2 at the interface [10]. In this paper, λ_1=0.6062, λ_2=0.9989. The stress σ_θ at r direction ($\theta=0$) can be expressed as follows. The notation r denotes the radial distance away from the corner singular point O.

$$\sigma_\theta = \frac{K_{\sigma,\lambda_1}}{r^{1-\lambda_1}} + \frac{K_{\sigma,\lambda_2}}{r^{1-\lambda_2}} \cong \frac{K_{\sigma,\lambda_1}}{r^{1-\lambda_1}}\left(1+C_\sigma\, r^{\lambda_2-\lambda_1}\right) \tag{1}$$

Here, K_{σ,λ_1} and K_{σ,λ_2} are the intensities of the singular stress field. The intensities of singular stress field can be obtained based on our previous study[11,12] by using Reciprocal Work Contour Integral Method[13] (RWCIM). The intensities of the singular stress field can be represented with only K_{σ,λ_1} since C_σ is almost constant expressed as $C_\sigma = -5.2387 \pm 0.2659$.

In this study, the thick specimens used by Park [9] in Fig.3 are analyzed where the adherends aluminum alloy 6061-T6 (Young's modulus E =68.9 [GPa], Poisson's ratio ν =0.3) are bonded with adhesive FM73 M epoxy (Young's modulus E =4.2 [GPa], Poisson's ratio ν =0.45). The typical force-displacement curves of the adhesive joints show nearly linear behavior. A drop in load was used to detect a failure. The total length of the specimen is 225mm, adherend thickness t_1 =7mm, d =10mm, adhesive thickness t_{ad} =0.15~0.9mm, adhesive length l_{ad} =20~50mm, L =50mm, σ_o =1MPa (P =14.15N).

Fig.4 shows the $K_{\sigma c}$ with different l_{ad} and t_{ad} under $P=P_{af}$. Here, P_{af} is the fracture load, "A25" means l_{ad} =25mm and t_{ad} =0.15mm, "A25-30" means l_{ad} =25mm and t_{ad} =0.30mm, and so on. It is found that the average value of $K_{\sigma c}$ is 4.030 $\mathrm{MPa \cdot m^{1-\lambda_1}}$, and the $K_{\sigma c}$ values are almost constant independent of the l_{ad} and t_{ad}. It is seen that the adhesive strength can be expressed as $K_{\sigma c}$ =const.

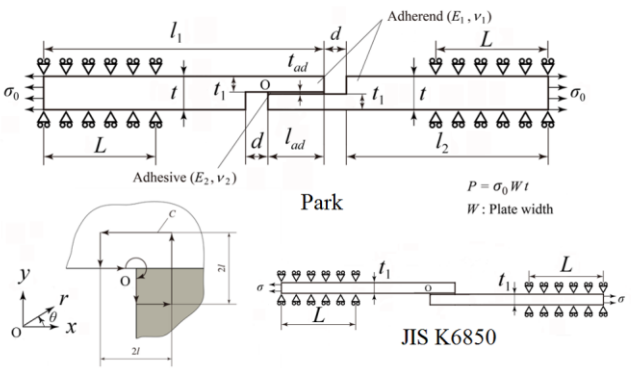

Fig. 3 Analysis model and boundary condition.

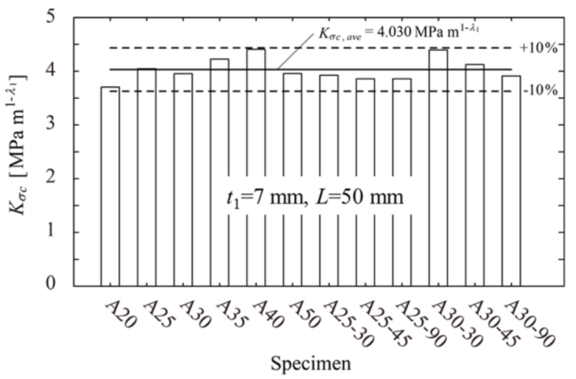

Fig. 4 Adhesive strength expressed as $K_{\sigma c}$ =const for t_{ad} =0.15~0.9mm and l_{ad} =20~50mm under fixed t_1 =7mm, L =50mm.

3 PURE SHEAR TESTING TO MINIMIZE K_{σ,λ_1}

The butt joint in Fig.1 is used to obtain the adhesive strength under pure tension [5, 6] and the single lap joint in Fig.2 is used to obtain the adhesive strength under pure shear. However, due to the deformation of single lap joint during testing, peeling force as well as shearing force is applied to the adhesive region. Then, the intensity of singular stress K_{σ,λ_1} is also affected by the peeling force due to the deformation. Since the single lap joint testing should be done under pure shear loading, smaller K_{σ,λ_1} is desirable. The fracture load P_{af} increases with increasing the adhesive length l_{ad} as described in [9], and the adhesive strength can be expressed as $K_{\sigma c}$ =const independent of adhesive geometry l_{ad} and t_{ad}. This means that when K_{σ,λ_1} is small, the fracture load P_{af} is large. Therefore, in order to minimize K_{σ,λ_1}, the effect of specimen geometry is considered under the same adhesive geometry and load P. In this section, we assume P =14.15N, the adhesive length l_{ad} =25mm, and adhesive thickness t_{ad} =0.15mm. Then, the effects of specimen geometries t_1 (adherend thickness) and L (fixed boundary length) on the intensity of singular stress field K_{σ,λ_1} are discussed.

Figure 5 shows the relationship between the intensity of singular stress field K_{σ,λ_1} and adherend thickness t_1 under different fixed length L. The dashed line shows the minimum value of K_{σ,λ_1}. Here, JIS* means only the adherend thickness t_1 =1.5mm and fixed boundary length L =50mm in JIS K6850 are used as shown in Fig.3. As can be seen from Fig.5, the K_{σ,λ_1} decreases with increasing t_1 and L. The K_{σ,λ_1} value becomes constant if t_1 is large enough. The $K_{\sigma,\lambda_1}|_{t_1=1.5\text{mm}}$ (JIS K6850) is 5 times larger than the one of $K_{\sigma,\min}$, and the $K_{\sigma,\lambda_1}|_{t_1=7\text{mm}}$ [9] is more than twice than that of $K_{\sigma,\min}$. It is seen that the specimen in [9] is better than the JIS, but it is more desirable to use larger adherend thickness.

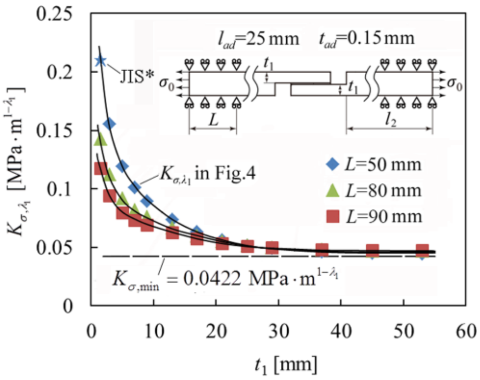

Fig. 5. Effect of L and t_1 on K_{σ,λ_1} under fixed l_{ad} and t_{ad} (JIS*: Only t_1 =1.5mm and L =50mm in JIS K6850 are used as shown in Fig.3).

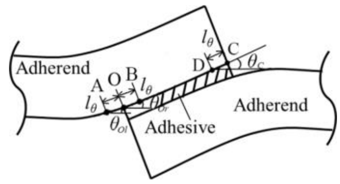

Fig.6. Definition of deformation angle.

4 DEFORMATION ANGLE AT THE INTERFACE CORNER

As shown in section 3, the intensity of singular stress K_{σ,λ_1} decreases with increasing the adherend thickness t_1. It is found that the minimum K_{σ,λ_1} can be obtained when t_1 is large enough. In this section, the deformation angle at interface corner is considered by changing the distance l_θ.

Fig. 6 shows the deformation example near the interface corners. In order to obtain the deformation angle, two target points are considered. For the deformation angle θ_{ol} at interface corner O, two target points are points O and A with the distance l_θ. For the deformation angle θ_{or} at interface corner O, two target points are points O and B with the distance l_θ. Fig. 7 shows the deformation angles θ_{ol} and θ_{or} vs. l_θ under t_1 =7mm. It is found that the values of θ_{ol} and θ_{or} both increase with increasing l_θ, and the difference between θ_{ol} and θ_{or} increases with decreasing l_θ. Therefore, we cannot obtain the maximum deformation angle at corner O. Fig. 8 shows the deformation angle θ_C vs. l_θ under t_1 =7mm. It is seen that the value of θ_C increases initially with increasing l_θ and then decreases. Then, the maximum θ_C can be obtained when l_θ =1/3^{3}mm. Thus, in this study, the deformation angle will be considered by using the maximum deformation angle at corner C rather than at corner O.

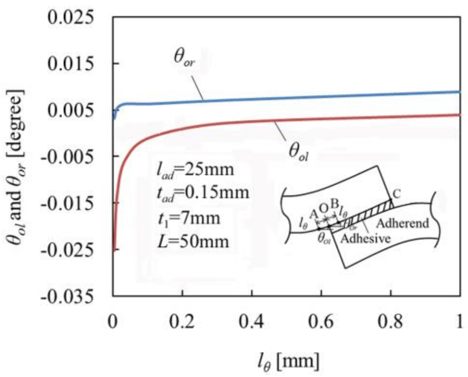

Fig. 7 Deformation angle at corner edge O.

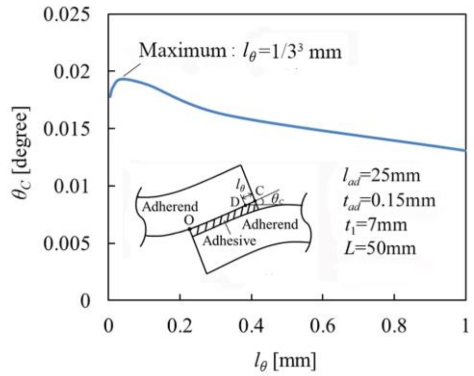

Fig. 8 Deformation angle at corner edge C.

As can be seen from Fig. 5, the minimum K_{σ,λ_1} can be obtained when t_1 is large enough. Similar to the variation trend of K_{σ,λ_1}, the minimum θ_C can be obtained when the adherend thickness t_1 is large enough.

5 CONCLUSION

In this study, the adhesive strength for single lap joint is investigated based on the intensity of singular stress field. Since the experiments are often time-consuming and costly, the analysis method shown in this paper can help to predict the strength of adhesive joint accurately and conveniently. The conclusions can be summarized in the following way.

(1) In this paper, the critical intensity of singular stress field $K_{\sigma c}$ is investigated by using the analysis method presented. It is seen that the adhesive strength can be expressed as $K_{\sigma c}$ =const.

(2) The effects of specimen geometries t_1 (adherend thickness) and L (fixed boundary length) on the intensity of singular stress field K_{σ,λ_1} are discussed. The results show that the K_{σ,λ_1} at the interface corner decreases with increasing the t_1, and the minimum intensity of singular stress field $K_{\sigma,\min}$ can be obtained when t_1 is large enough.

(3) The deformation angle at the interface corner is investigated by using the maximum deformation angle at interface corner C. It is found that the minimum deformation angle θ_C can be obtained when the adherend thickness t_1 is large enough.

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